

# Maximizing the Gradient Sum of an RF Station Using Simulation

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# Outline

## Problem statement

## Proposed approaches

- A. indiv.  $Q_L$ , indiv.  $P_K$ , calibrated for **max** beam
- B. same  $Q_L$ , indiv.  $P_K$ , calibrated for **no** beam
- C. indiv.  $Q_L$ , indiv.  $P_K$ , calibrated for **any** beam

## Examples

**FLASH** – 9mA test at DESY

**HINS** – using Ferrite Vector Modulator and klystron  $A/\Phi$  modulation

## Conclusion

# Problem Statement

System: **one** klystron for **many** cavities

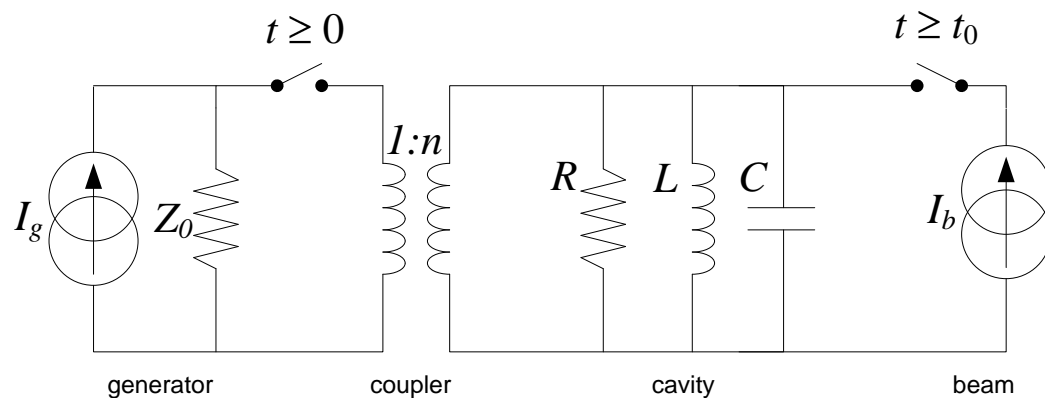
Cavities in a cryomodule  
have **different quenching** gradients  
operate at **different gradients**

Motivations:

- Can a **flat top** vector sum be achieved ? Which gradient ?
- How to choose  $Q_L$ ,  $P_K$ ,  $\psi$  for all cavities ?
- Operate from 0 to full beam current and prevent cavity quench
- Enough klystron **power** ?

# Simulation Model

Standard **RLC cavity model**:



Solving the RLC electrical model of a cavity  $\rightarrow$  2<sup>nd</sup> order differential equation \*

$$\ddot{\mathbf{V}}(t) + \frac{\omega_0}{Q_L} \dot{\mathbf{V}}(t) + \omega_0^2 \mathbf{V}(t) = \frac{\omega_0 R_L}{Q_L} \dot{\mathbf{I}}(t)$$

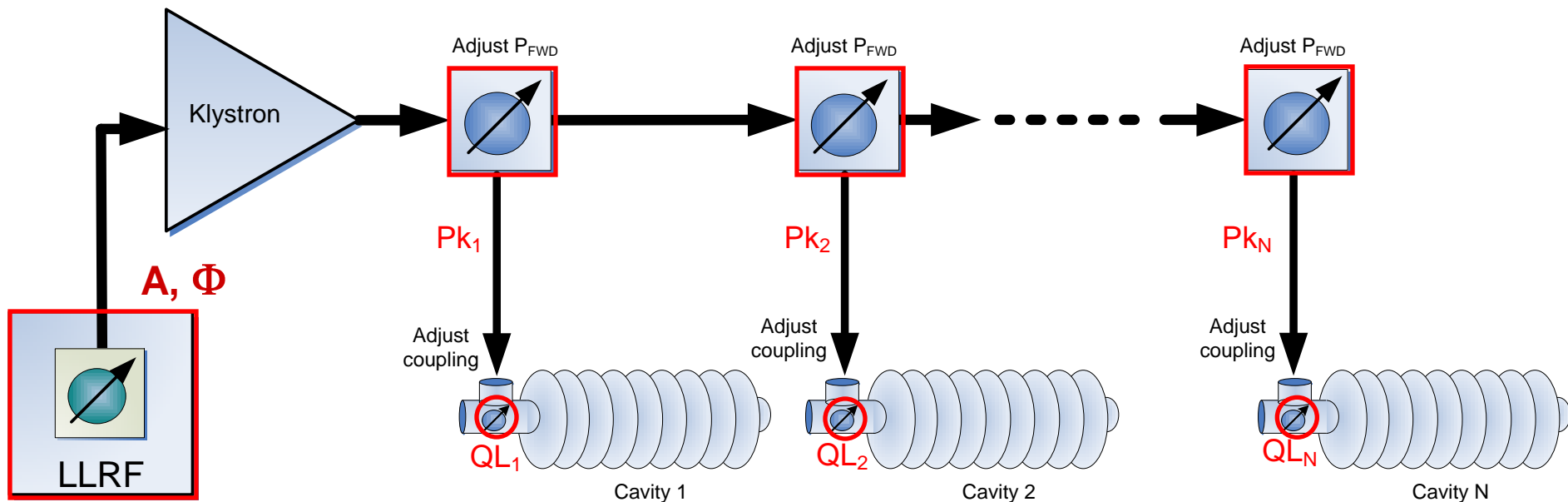
**1<sup>st</sup> order solution** to the equation above:

$$\frac{d}{dt} \begin{pmatrix} V_r \\ V_i \end{pmatrix} = \begin{pmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} V_r \\ V_i \end{pmatrix} + \begin{pmatrix} R_L \omega_{1/2} & 0 \\ 0 & R_L \omega_{1/2} \end{pmatrix} \cdot \begin{pmatrix} I_r \\ I_i \end{pmatrix}$$

\* “Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities” , T. Schilcher PhD Thesis, 1998

# Problem Statement

- 3 knobs:
- LLRF
  - cavity coupler
  - waveguide power coupler

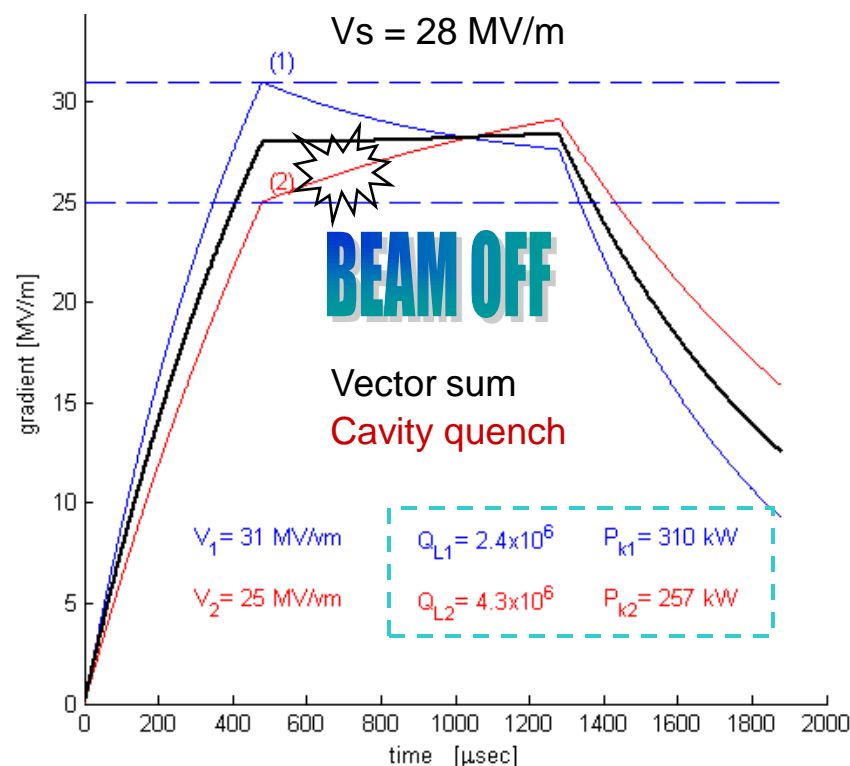
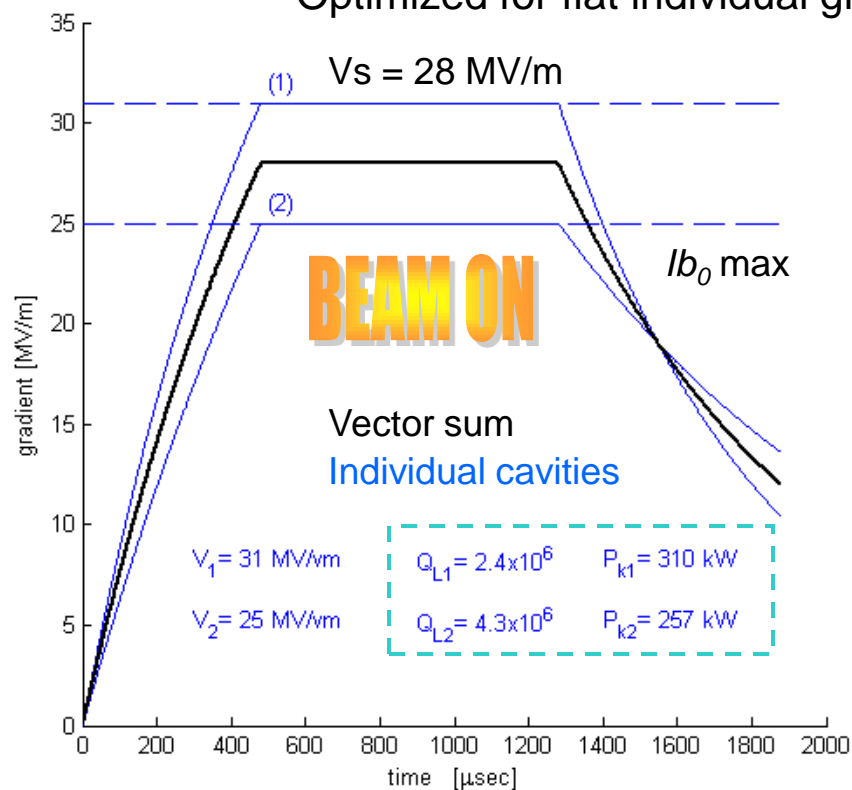


# 1<sup>st</sup> approach: individual $Q_L$ , individual $P_K$ (optimized for max beam)

$$\frac{V}{V_0} = \frac{Q_L}{Q_{L0}} \left( 2^{\frac{Q_{L0}}{Q_L}} - 1 \right)$$

$$\frac{P_k}{P_{k0}} = \frac{Q_L}{Q_{L0}} 4^{\left( \frac{Q_{L0}}{Q_L} - 1 \right)}$$

Optimized for flat individual gradient under maximum beam current



REFERENCE:

*“RF distribution optimization in the main linac of the ILC”*  
K.Bane, C.Adolphsen, C.Nantista (PAC07)

# 2<sup>nd</sup> approach: same $Q_L$ , individual $P_K$ (optimized for no beam)

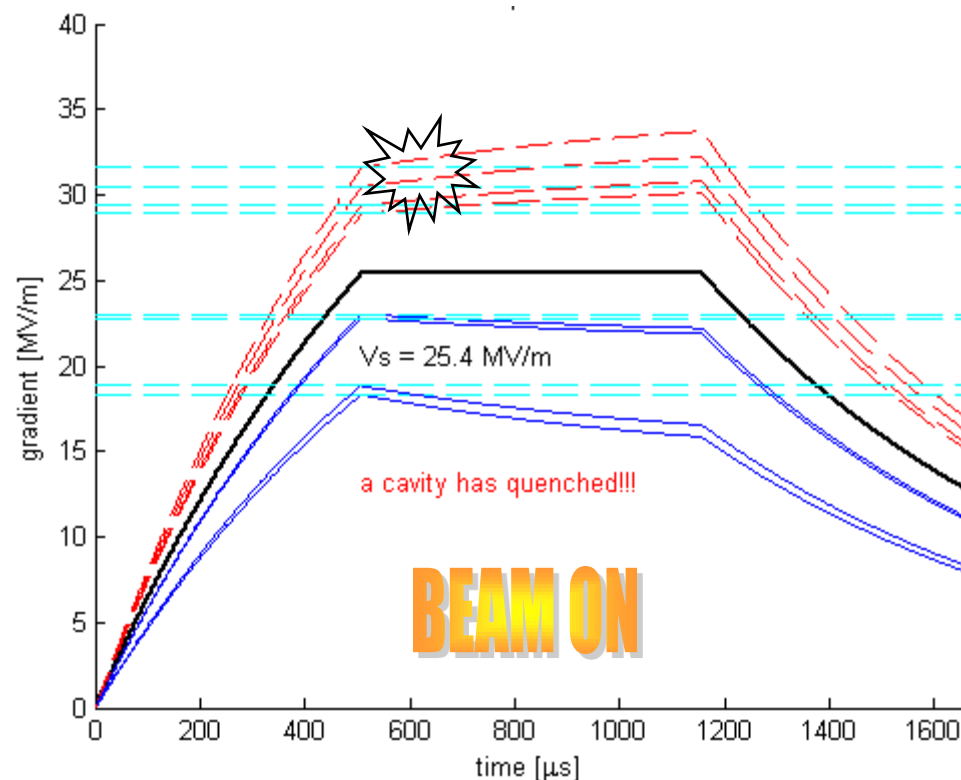
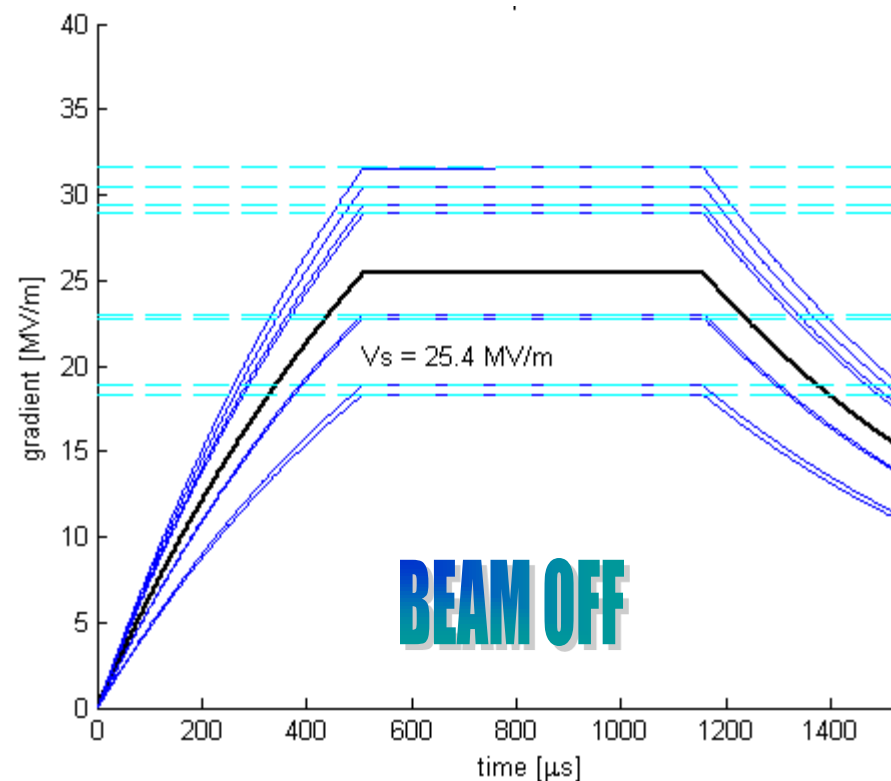
Same  $Q_L$  for all cavities ( $Q_L = 3 \times 10^6$ )

ACC6 : [30.48 31.59 29.41 28.91 18.32 18.84 23.04 22.80] MV/m

$I_{bo} = 5$  mA,

beam pulse = 0.65 ms

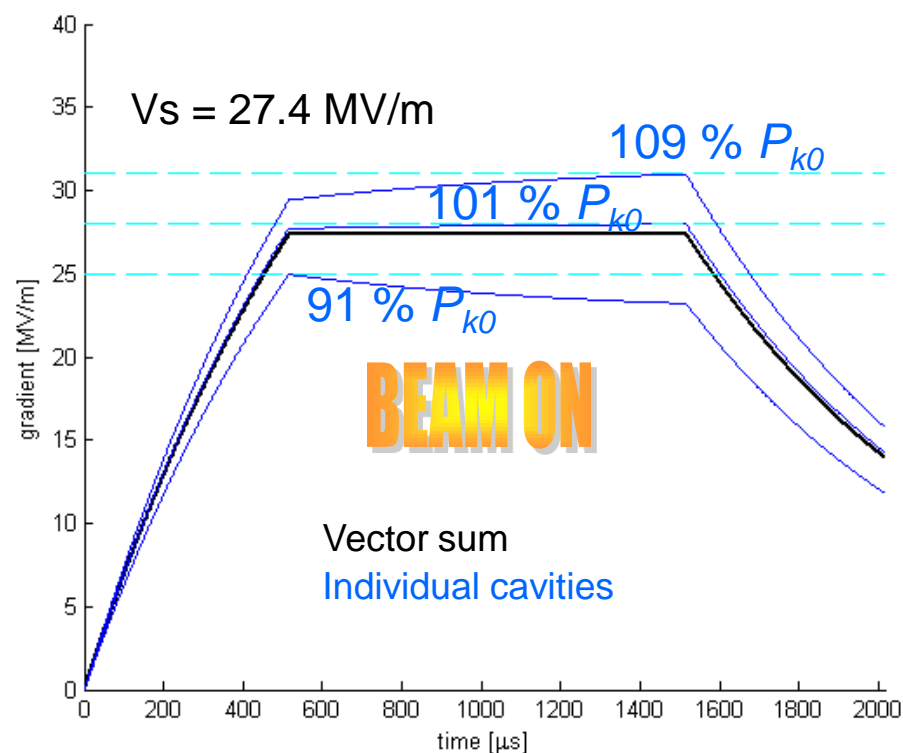
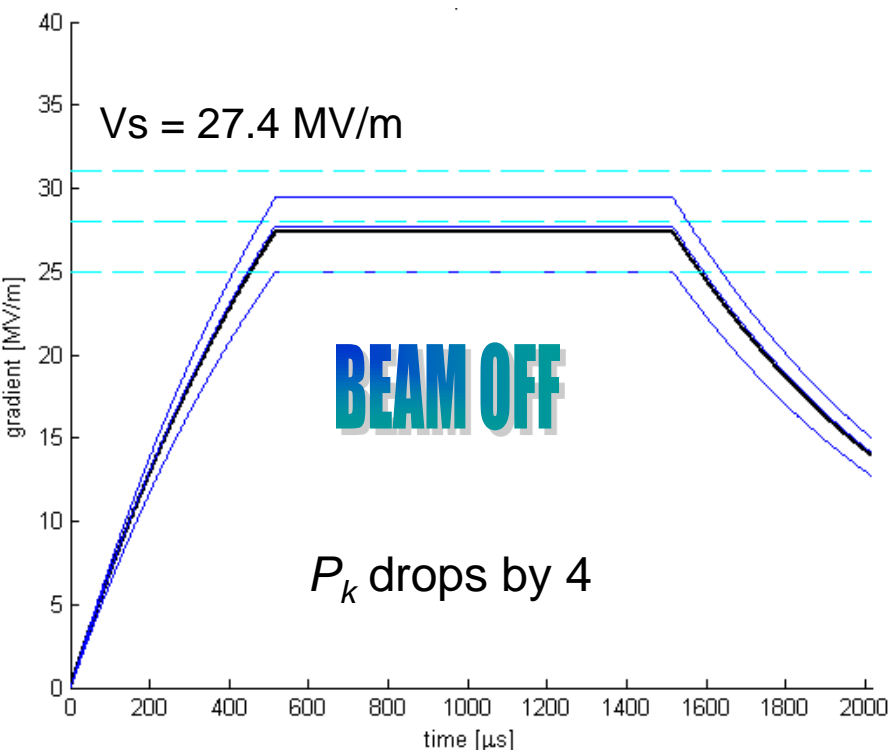
Adjust power to set cavities at maximum gradient without beam



REFERENCE:

“XFEL waveguide distribution and more”, V. Katalev,  
XFEL HLRF kick off meeting, 2007

“Optimized”: same  $Q_L$ , individual  $P_K$   
(optimized for any beam current)



REFERENCE:

“Operational Solution to Obtaining a Flat Vector Sum from Multiple Cavities with Gradient Disparities”, J. Branlard, B. Chase, FNAL ILC DB doc # 480



# Example 1: FLASH 9mA test at DESY

“no-beam” study - 8/27/2009

Simulator mimics power distribution & coupling for ACC4, 5 and 6

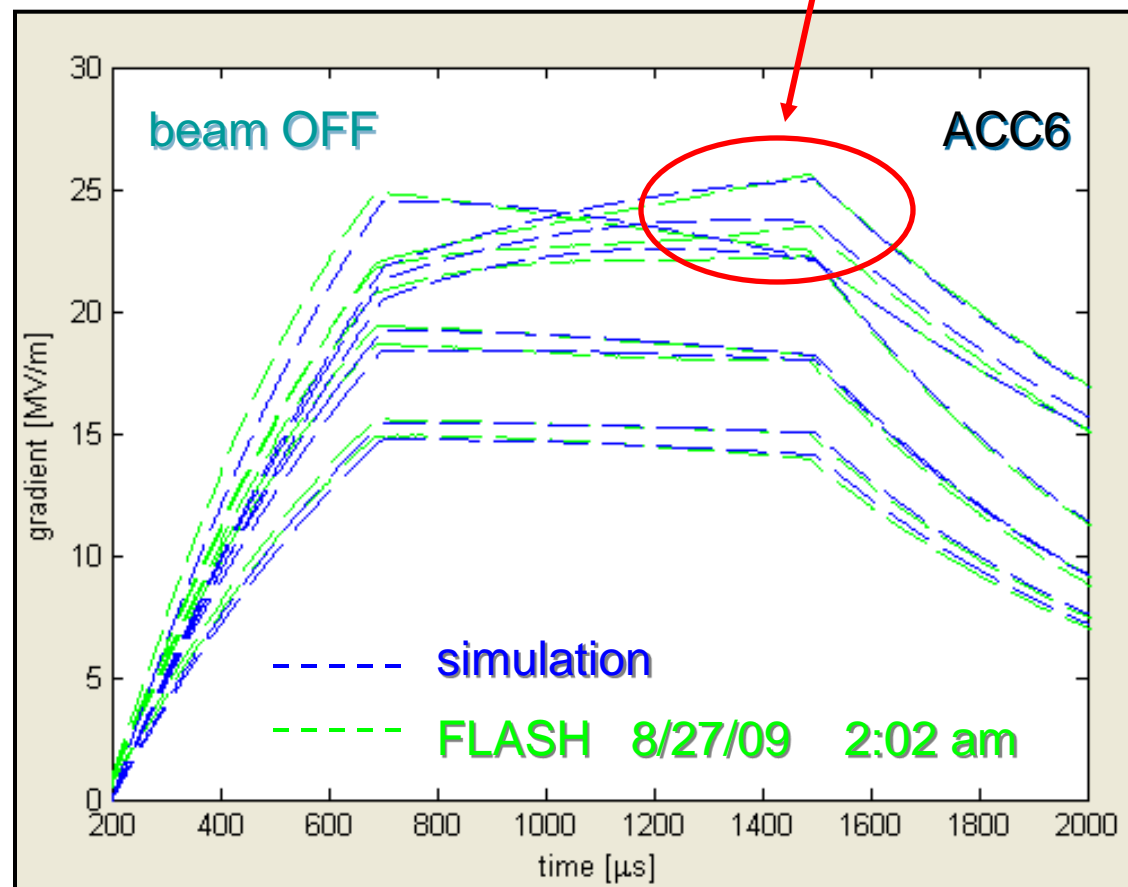
Verification of simulated cavity gradients vs. experimental data without beam

Using simulator, predict behavior with 9 mA beam current

Using simulator, propose tuning scheme to avoid quench of “high-gradient” cavities

Implement scheme and verify cavity tilts

cavities with adjusted coupler values



tilt up without beam → flat with beam

# Example 1: FLASH 9mA test at DESY

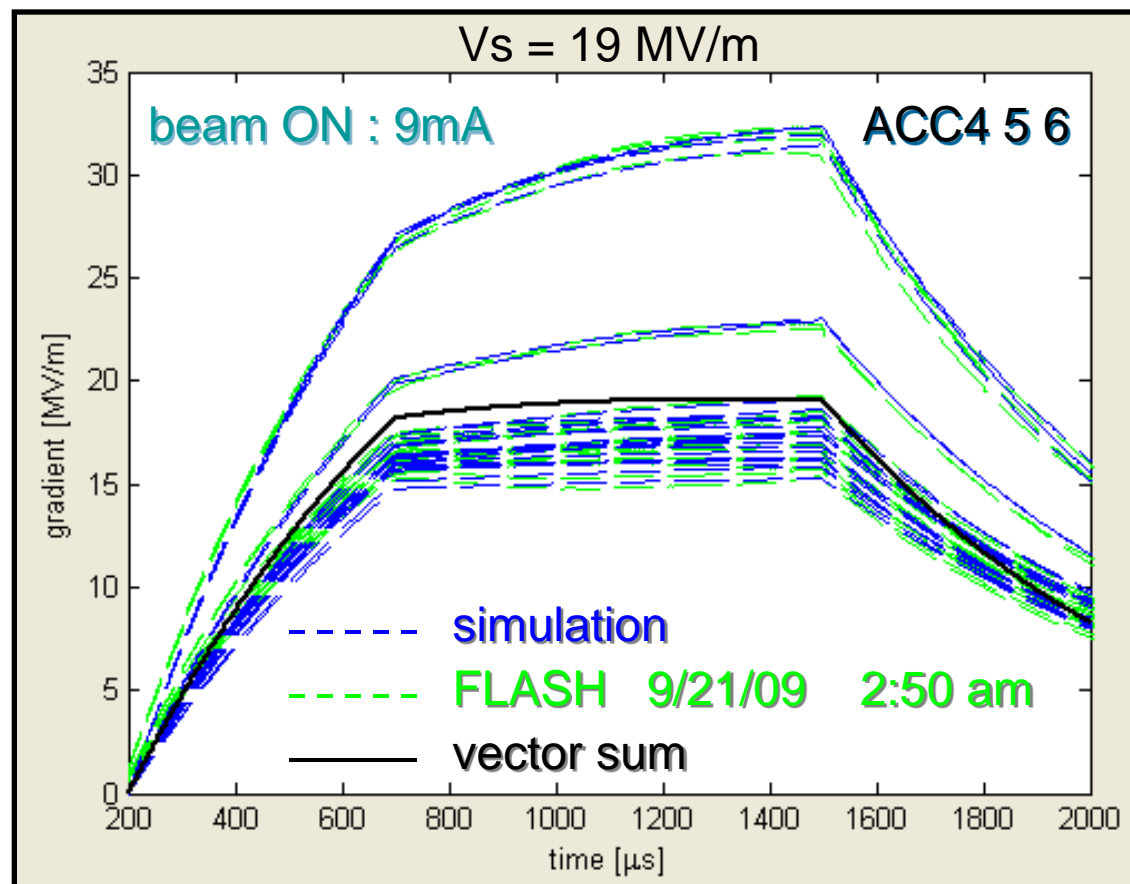
“high beam” study - 9/21/2009

Verification of model against experimental data with 9mA beam

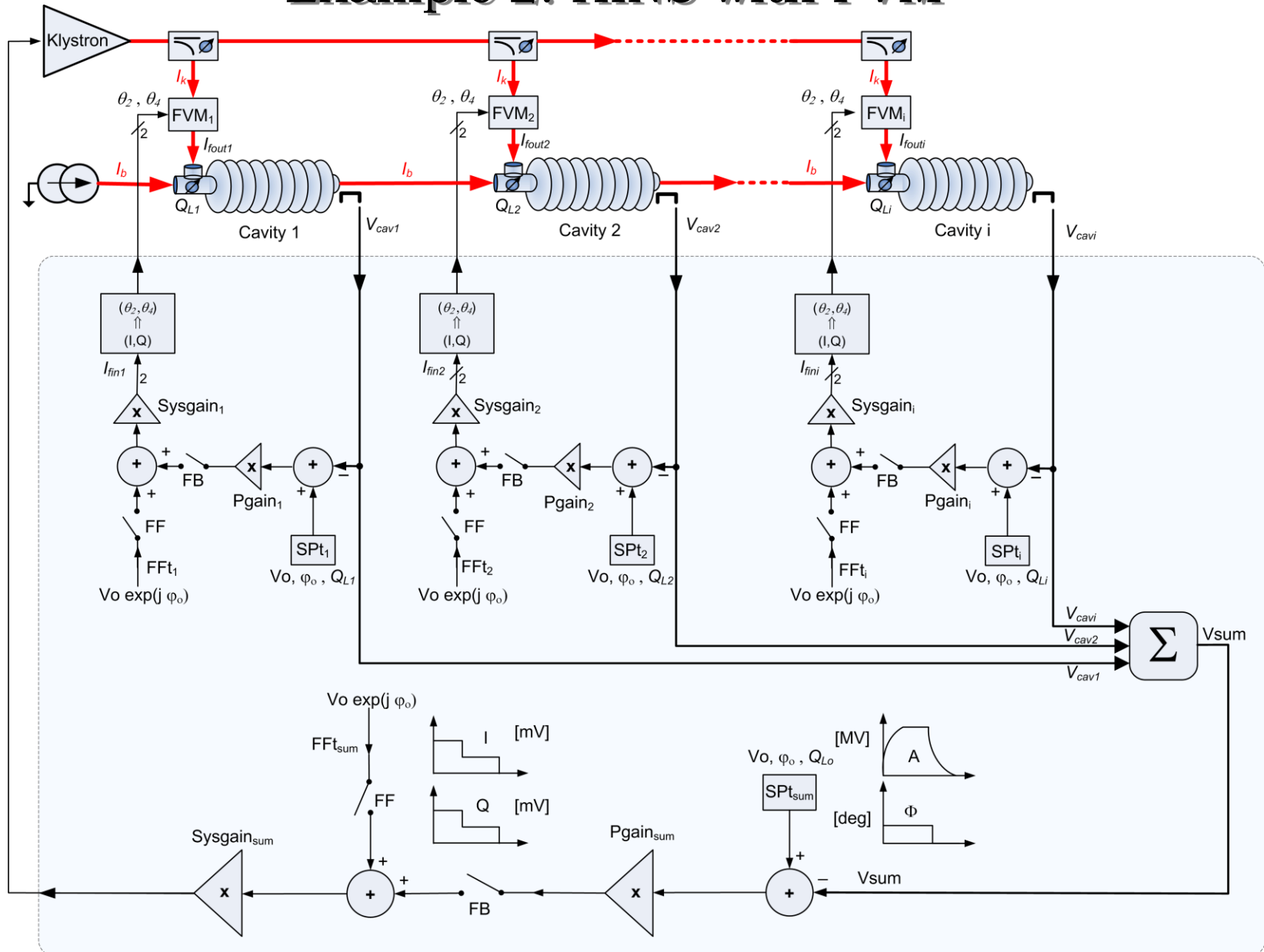
Could not implement optimized scheme with beam

→ lowered klystron power for safe operation

Validate simulator as useful tool for next test



# Example 2: HINS with FVM



# Example 2: HINS with FVM

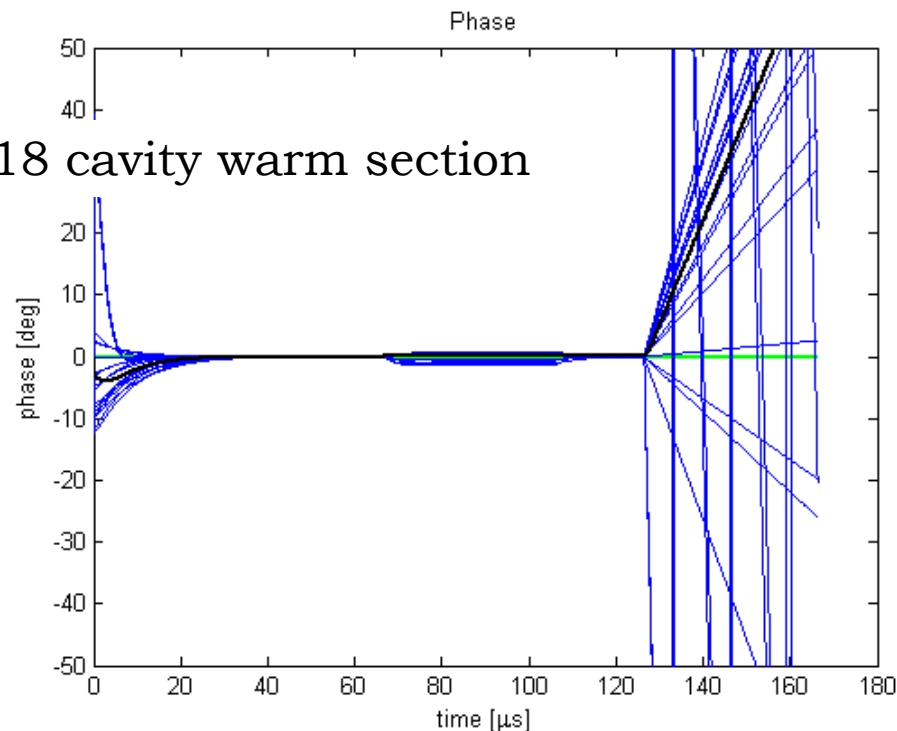
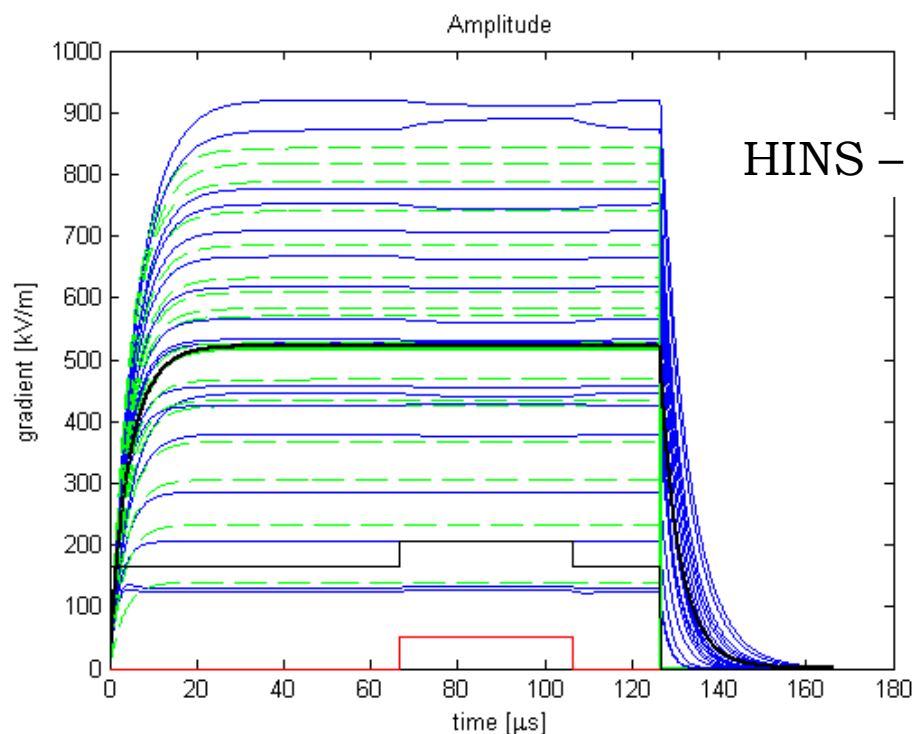
detuning error ( $\delta\omega$ )	$\delta\omega = 2\pi \times 2.5\text{kHz} (\sim 6\%)$
loaded Q error ( $\delta Q_L$ )	$\delta Q_L = 500 (\sim 12\%)$

**FF only** vector sum amplitude error: 2%

vector sum phase error:  $0.5^\circ$

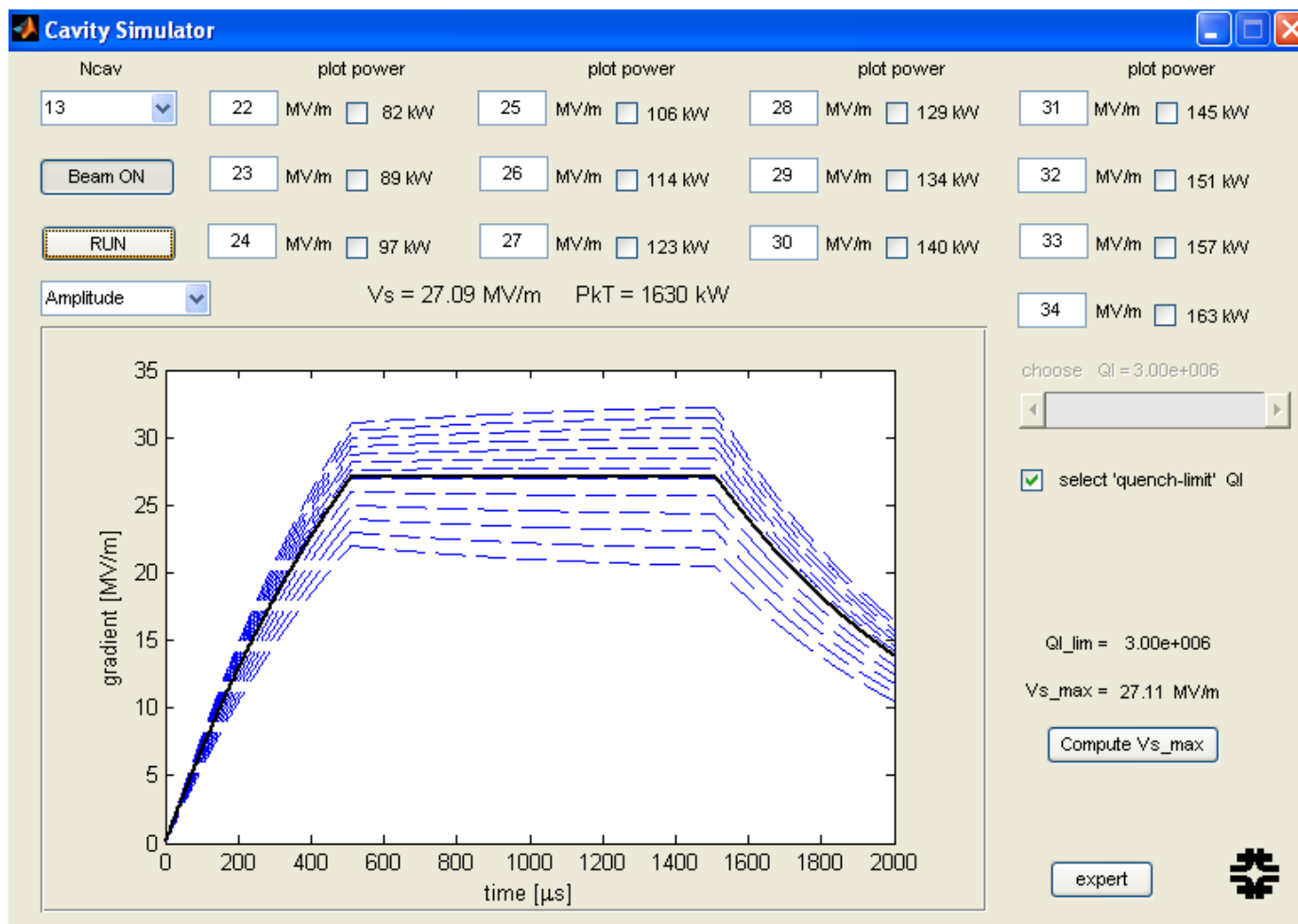
**FB (PI)** vector sum amplitude error:  $<0.01\%$

vector sum phase error:  $<0.01^\circ$



# MATLAB cavity simulator

Available for download from the FNAL ILC database: [doc#481](#) (zipped Matlab files)



Related paper:

[FNAL ILC DB doc # 480](#)

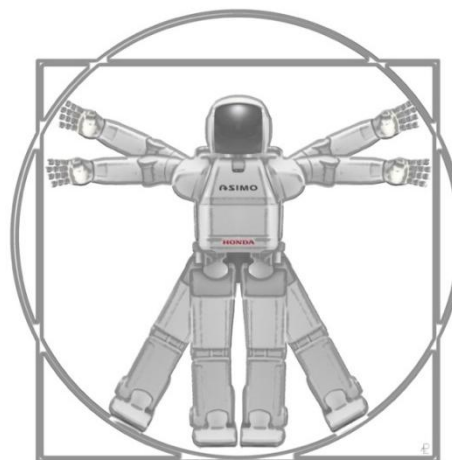
# Conclusions

Simulation valuable tool to understand **complex systems**

Easy to modify/improve model structure and parameters

Accurately predictive (control algorithms + FVM)

Simulation results are only  
**as good as** the model



Complete **MACRO** model

v.s.

Targeted **MICRO** model

どうもありがとう。

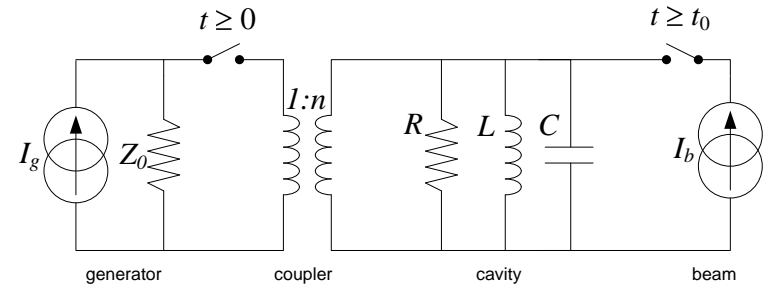
Thank you!

**BACK UP  
SLIDES**

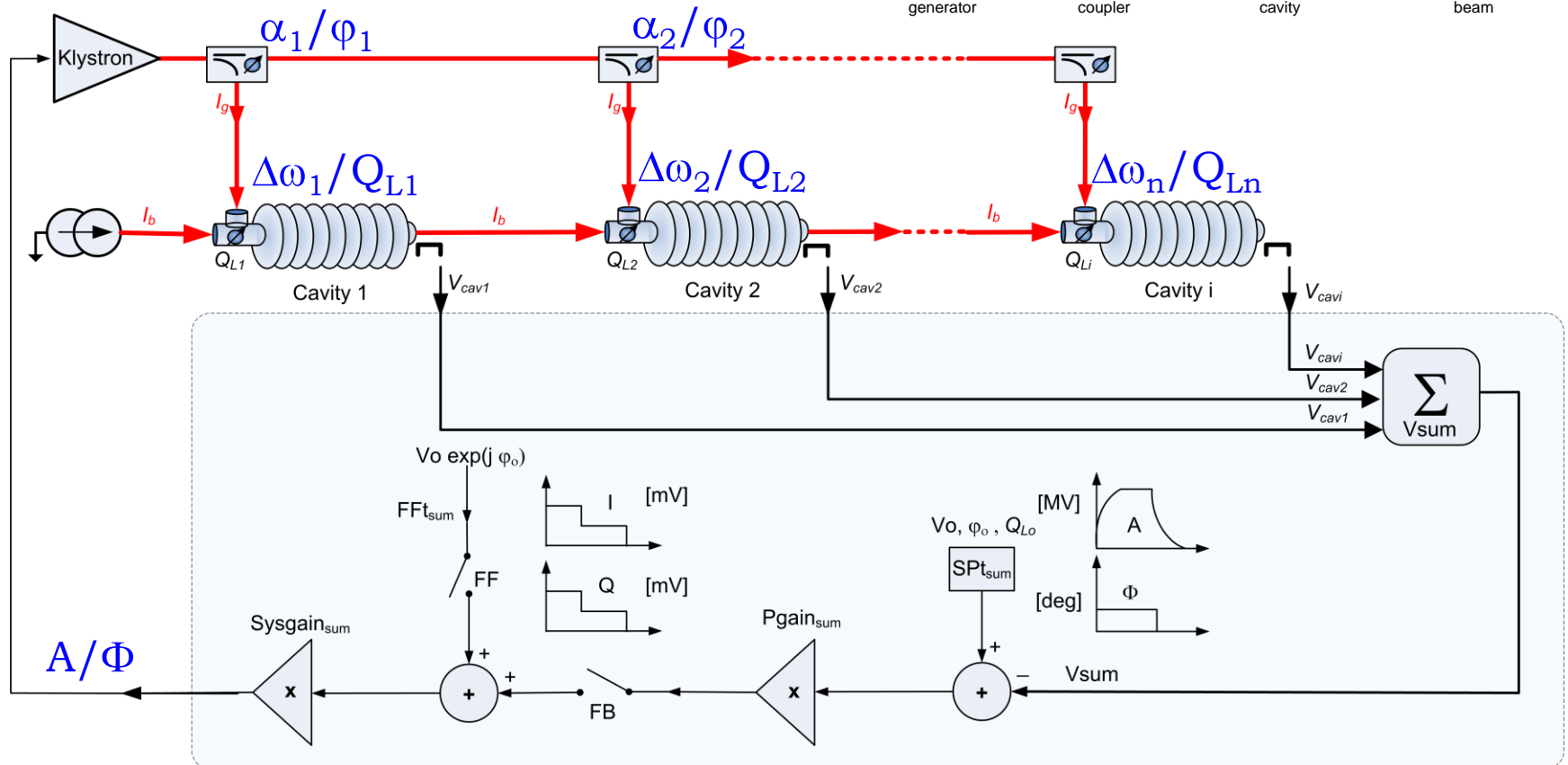


# Simulation Model

Standard RLC cavity model:



Klystron FF SP table/FB loop:



# Simulation Model

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$V_{cav} = (V_r + j.V_i)$  is a function of the cavity detuning  $\Delta\omega$ , the cavity half bandwidth  $\omega_{1/2}$ , the cavity loaded resistance  $R_L$  and the current inside the cavity  $I_t = I_g + I_b = (I_r + j.I_i)$

\* “Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities” , T. Schilcher PhD Thesis, 1998

# Impact of the **cavity gradient distribution** for a fixed 22-34 MV/m spread

- 5.5 %

- 3.2 %

- 2 %

28.00 MV/m

26.45 MV/m

27.11 MV/m

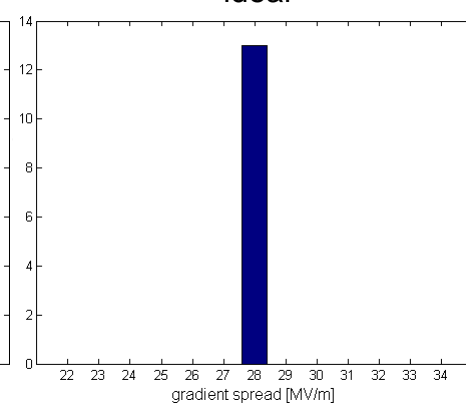
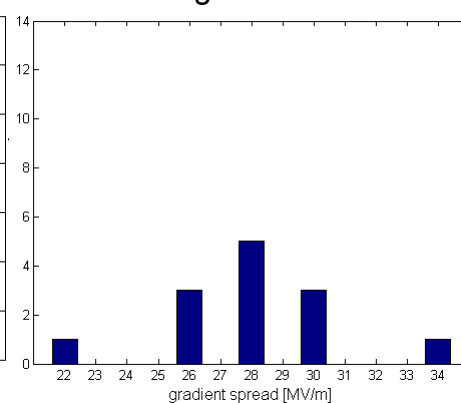
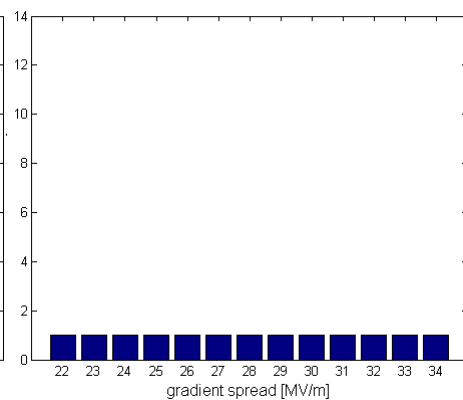
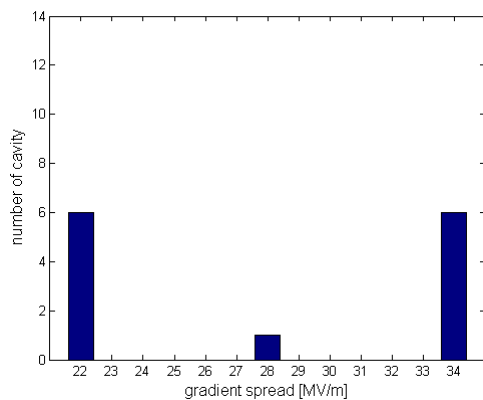
27.44 MV/m

extremes

uniform

“gaussian”

ideal



# Approach comparison

Approach	A	B	C
Tuning scheme	indiv. $Q_L$ , indiv. $P_K$	same $Q_L$ , indiv. $P_K$	same $Q_L$ , indiv. $P_K$
Calibrated for	<b>MAX</b> beam	<b>NO</b> beam	<b>ANY</b> beam
Individual cavity gradient with MAX beam	Flat	Tilt, <b>QUENCH</b>	Tilt
Individual cavity gradient with NO beam	Tilt, <b>QUENCH</b>	Flat	Flat
Main advantage	Maximum achievable gradient	Easy to tune	Same gradient for ANY beam current
Main drawback	Requires lower operating gradient for <b>LOW</b> beam currents	Requires lower operating gradient for <b>HIGH</b> beam currents	Operating gradient is lower than maximum achievable